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X-ray spectral transitions of black holes from *RXTE* All-Sky Monitor

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ABSTRACT

We have analysed X-ray outbursts from several Galactic black hole (GBH) transients, as seen by the All-Sky Monitor (ASM) on board *Rossi X-ray Timing Explorer* (*RXTE*). We have used the best estimates of distance and black hole mass to find their luminosity (scaled to the Eddington limit), which allowed for direct comparison of many sources. We have found two distinct hard-to-soft state transitions in the initial part of the outburst. The distinction is made on the basis of the transition luminosity, its duration, the shape of the track in the hardness-luminosity diagram, and evolution of the hardness ratio. The bright/slow transition occurs at ∼30 per cent of Eddington (estimated bolometric) luminosity and takes ≳30 days, during which the source quickly reaches the intermediate/very high state and then proceeds to the soft state at much slower pace. The dark/slow transition is less luminous (≲10 per cent of Eddington), shorter (≲15 days) and the source does not slow its transition rate before reaching the soft state. We speculate that the distinction is due to irradiation and evaporation of the disc, which sustains the Comptonizing corona in the bright intemediate/very high state.

Key words:
accretion, accretion discs – instabilities – X-rays: binaries

1 INTRODUCTION

Black holes are remarkably simple objects, entirely characterized by their mass and spin, so we should expect similar appearance of their accretion flows. In Galactic binaries black holes have comparable masses, so the accretion flow properties should be then determined by their spin and (instantaneous) accretion rate. It has been established recently that the accretion rate history plays an important role in shaping the accretion flow as well (e.g. van der Klis 2001; Maccarone & Coppi 2003). The inclination angle can also have some, but rather weak, effect on the observed properties, due to anisotropy of the disc or corona emission. Most of these effects can be easily accounted for: the mass by scaling the observed luminosity to Eddington ($L_{\rm Edd}$) limit, the accretion history by tracing the entire outburst of a transient, the inclination angle effects are easy to understand within existing models of accretion. Perhaps the most challenging are the effects of black hole spin as they involve the properties of the accretion flow near and below the last stable orbit (e.g. Done & Gierliński 2006).

GBHs are observed in several distinct X-ray spectral states (see Zdziarski & Gierliński 2004; McClintock & Remillard in press and references therein). This is best seen in X-ray transients undergoing occasional outbursts, when their accretion rate (and luminosity) can change by several orders of magnitude. With varying accretion rate the X-ray spectrum can also change dramatically, passing through various states on timescales from days to months. These spectral transitions are probably the result of changes in the geometry of the accretion flow (for a review see Done & Gierliński 2004).

Typically, a transient begins its outburst in the low/hard (LH) state, where its spectrum can be roughly described by a hard (photon spectral index $\Gamma \sim$ 1.5–2) power law with high-energy cutoff at $\sim$ 100 keV (e.g. Wilson & Done 2001). The LH state can be seen at luminosities up to $\sim$0.2 $L_{\rm Edd}$ during the rise of an outburst (Done & Gierliński 2003), but is less bright ($\lesssim$0.04 $L/L_{\rm Edd}$) in the decaying part of the outburst (Maccarone 2003). A truncated disc, replaced by the optically thin, hot, Comptonizing inner flow can explain the hard state (e.g. Poutanen, Krolik & Ryde 1997; Esin et al. 2001), but other geometries have been also proposed (e.g. Young et al. 2001; Beloborodov 1999).

After the initial LH state the X-ray spectrum usually undergoes transition into the high/soft (HS) state, via intermediate (IM) or very high (VH) state. The X-ray spectrum is then dominated by the disc emission of temperature of $\sim$ 1 keV, accompanied by a soft ($\Gamma \sim$ 2–2.5) power-law tail to higher energies. In the soft state the cold disc probably extends down to or near the last stable orbit and the hard component is produced by Comptonization in active regions or corona above the disc surface (e.g. Gierliński et al. 1999).

The IM/VH state is characterized by a soft X-ray spectrum dominated by a steep ($\Gamma \sim$ 2.5) power law, extending to several

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hundred keV without apparent cutoff (Grove et al. 1998). Initially it was recognized as the brightest state of a given object (Miyamoto et al. 1991), but HS states brighter then IM/VH state were seen (e.g. Zdziarski et al. 2001). IM/VH state has been observed in various sources at a wide range of luminosities of $\sim$0.01–1 $L_{\rm Edd}$. Another characteristic feature of IM/VH state is strong rapid aperiodic variability often accompanied by a distinct quasi-periodic oscillation.

The IM/VH state is typically related to the transitions between the hard and soft states (Rutledge et al. 1999). In many transients it has been seen after the initial hard state, when the source reached high luminosity ($\gtrsim$0.1 $L_{\rm Edd}$). This intermediate phase can last up to several dozen days before the source moves to the standard HS state. There are, however, instances of IM/VH state observed during 'failed' transitions or between two periods of the soft state (e.g. Homan et al. 2001; Kubota & Done 2004).

The X-ray spectral states and transitions of Galactic black holes were analysed from the *RXTE* spectral data by many authors (e.g. Sobczak et al. 2000; Homan et al. 2001; Done & Gierliński 2003; Fender, Belloni & Gallo 2004; Homan & Belloni 2005). A lot of work has been also done on the *RXTE* ASM data (e.g. Grimm, Gilfanov & Sunyaev 2002; Zdziarski et al. 2002; Maccarone & Coppi 2003; Šimon 2004; Zdziarski et al. 2004; McClintock & Remillard in press). However, few of these works attempted to discuss properties of spectral states in terms of absolute *luminosity*. In this paper we present the first systematic study of black hole X-ray spectral states, based on hardness and luminosity derived from *RXTE* ASM data. We use the best known estimates of distance and mass of accreting black holes to derive their luminosity as a fraction of $L_{\rm Edd}$. This allows us for direct comparison between different sources. We also trace *spectral evolution* during the outburst. Using these data we show that there are two distinct types of transition between the hard and soft spectral states in the initial part of the outburst.

2 DATA REDUCTION

We have analysed publicly available light curves of 8 Galactic black hole candidates from ASM (Levine et al. 1996) on board *RXTE* (Jahoda et al. 1996). These sources were selected because their data had statistics sufficient to build hardness-luminosity diagrams. We used one-day averages in three ASM energy bands, roughly corresponding to 1.5–3 keV, 3–5 keV and 5–12 keV. To allow for direct comparison between different sources, we converted the observed count rates into luminosities.

First, we calculated the energy flux in each ASM channel, adopting the method of Zdziarski et al. (2002), who built the ASM response matrix, comparing various pointed Cyg X-1 observations with ASM count rates. To check the validity of this method for the IM/VH spectral shape, which is the main topic of this paper, we have used the physical model fitted to the very high state *RXTE* spectrum of XTE J1550–564 (model HYB in table 4 in Gierliński & Done 2003). This model gave the 1.5–12 keV flux of 4.3×10^{-8} erg s^{-1} cm^{-2}, while the corresponding ASM data converted into flux resulted in 4.5×10^{-8} erg s^{-1} cm^{-2}, in excellent agreement with the pointed observation.

Then, we found the total 1.5–12 keV (isotropic) luminosity and expressed it as a fraction of Eddington luminosity [$L_{\rm Edd} = 1.26\times10^{38}$ $(M/{\rm M}_\odot)$ erg s^{-1}] using the best-known estimates of mass and distance, summarized in Table 1. We also calculated the hard flux (not count rate) hardness ratio, HR, of energy bands 5–12/3–5 keV. For clarity, we have discarded the data points with poor statistics (relative error on HR greater then 0.3) from hardness-luminosity diagrams.

3 RESULTS

For our analysis we have selected ten outbursts of the transients listed in Table 1. In Figs. 1 and 2 we present their light curves and hardness-luminosity (H-L) diagrams. In order to guide the eye and make comparison of various sources easier, we have copied a schematic shape of the H-L track of XTE J1550–564 1998 outbursts (shown in Fig. 1a) in all other H-L diagrams (the inverted Y-shaped curve).

Fig. 3 shows the evolution of the hardness ratio of these outbursts. The horizontal lines show positions of hard and soft branches. These lines were used to estimate the duration of the hard-to-soft transition, which was defined as the time between the last point on the hard branch and the first point on the soft branch. Certainly, this is – to some extent – arbitrary, since we have defined these branches by reading the diagrams. The soft branch (and hard branch, where possible) corresponds to hardness ratio which stabilized at a certain value. Where only one or a few points were available in the hard state, we used them as the hard-state HR. The position of each branch varies slightly from source to source, but in most cases they are easy to identify from the diagrams. We will discuss possible drawbacks of this method in Section 4.

We have estimated the transition luminosity as $L/L_{\rm Edd}$ at hardness of HR = 1.25. We also found the fluence of each outburst, defined as the dimensionless $L/L_{\rm Edd}$ integrated over the entire outburst (so it has units of time). We summarize these results in Table 2.

These results suggest existence of two different types of hard-to-soft state transition. The bright/slow (BS) transition [Figs. 1(a–d) and 3(a–d)] is characterized by the transition luminosity of $\sim$0.1 $L/L_{\rm Edd}$ and duration of $\gtrsim$30 days. In the H-L diagram they trace a semi-circular, anti-clockwise track between the LH and HS branches. The best examples of this transition are shown by XTE J1550–564 (1998 outburst) and XTE J1859+226. The dark/fast (DF) transition [Figs. 1(e–g) and 3(e–g)] is significantly dimmer ($\lesssim$0.05 $L/L_{\rm Edd}$) and faster ($\lesssim$15 days). In the H-L diagram they move on an almost straight line between the LH and HS branches. The best examples of this transition are shown by XTE J1650-500 and XTE J2012+381. The last column in Table 2 shows the derived type of the transition. We discuss the details of this categorization in Sections 3.1 and 3.2.

3.1 Bright/slow transition

Fig. 1(a) shows the light curve and hardness-luminosity diagram of the 1998 outburst of XTE J1550–564. Fig. 3(a) shows the evolution of its hardness ratio. This particular outburst had a very good *RXTE* coverage of pointed observations and its broad-band energy spectra were analysed in details (e.g. Sobczak et al. 2000; Gierliński & Done 2003; Kubota & Done 2004). It is known to cover all spectral states (e.g. Homan et al. 2001). In Figs. 1(a) and 3(a) we connect the data points of the initial part (first 76 days) of the outburst. The outburst began in the LH state (Wilson & Done 2001) on the right-hand branch in the H-L diagram (at HR $\sim$ 2.5). Then, as the luminosity increased, the spectrum softened fairly quickly and the source moved anticlockwise in the H-L diagram, reaching the top point corresponding to a bright flare in the light curve. This region in the H-L diagram corresponds to the IM/VH state (Gierliński &

Source Name	M ($M_\odot$)	D (kpc)
4U 1543–47	9.4 (7.4–11.4)^a	7.5 (7–8)^a
XTE J1550–564	10 (9.7–11.6)^b	5.3 (2.8–7.6)^b
XTE J1650–500	4 ($\lesssim$7.3)^c	2.6 (1.9–3.3)^d
GX 339–4	6 (2.5–10)^e	8 (6.7–9.4)^f
XTE J1739–278	[10]	8.5 (6–11)^g
H 1743–322	[10]	[8.5]
XTE J1859+226	[10]	7.6 (4.6–8)^h
XTE J2012+381	[10]	[8.5]

Table 1. The list of the sources used in this paper, together with assumed mass (M) and distance (D) estimates and their uncertainties. The numbers in square brackets refer to quantities that were not known in the time of writing of this paper and were assumed: mass of 10 $M_\odot$ and distance of 8.5 kpc. The numbered references are as follows: [a] Park et al. (2004) [b] Orosz et al. (2002) [c] Orosz et al. (2004) [d] Homan et al. (2006) [e] Cowley et al. (2002) [f] Zdziarski et al. (2004) [g] Greiner, Dennerl & Predehl (1996) [h] Hynes et al. (2002).

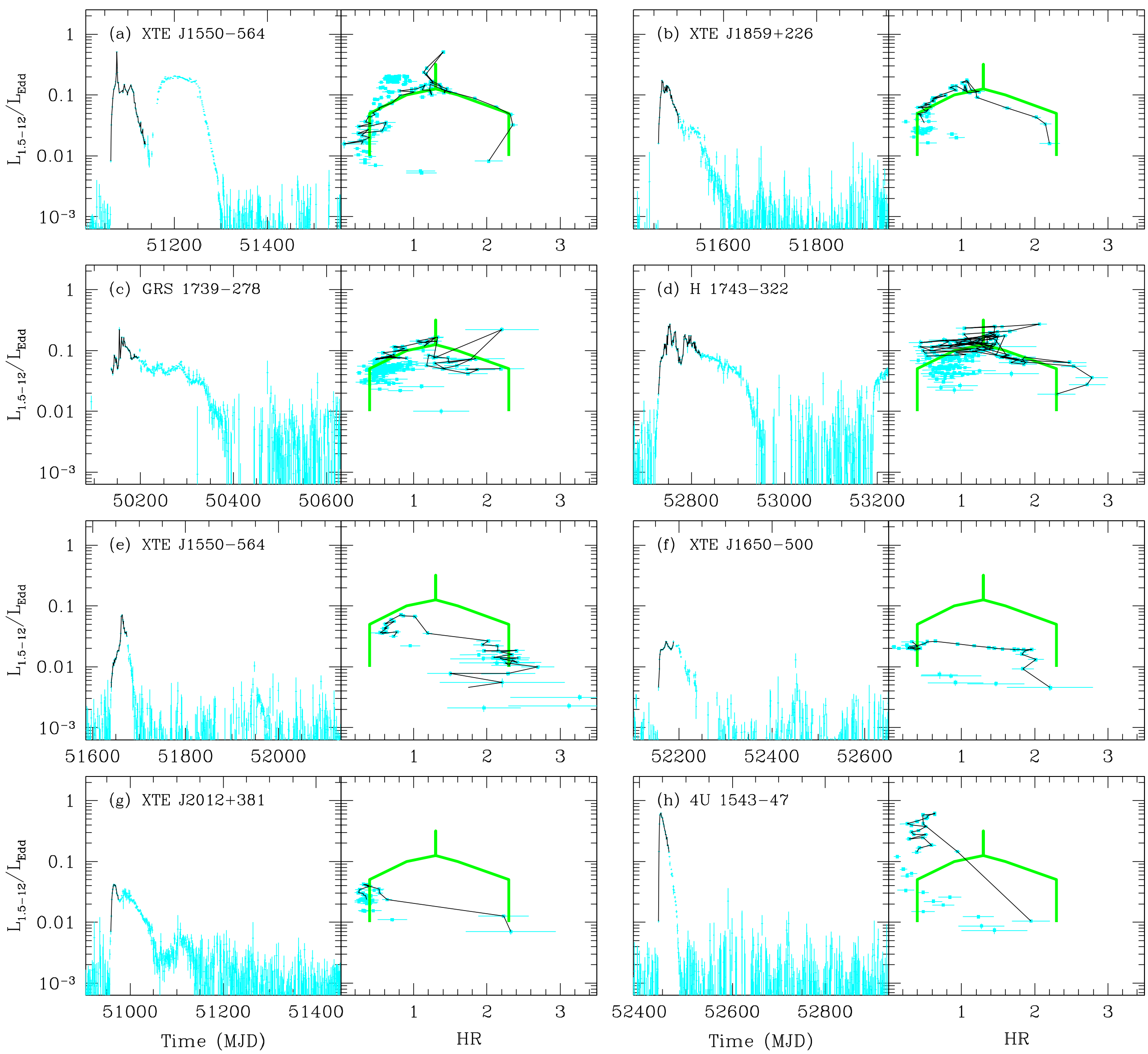

Figure 1. Light curves and hardness-luminosity diagrams of the outbursts of sources listed in Table 1, except for GX 339–4, which is shown in Fig. 2. The light curves are shown by light grey (cyan in colour) crosses. The thin black curve follows the transition from the hard to the soft state and joins the same data points in the light curve and H-L plot. The thick grey (green in colour) inverted y-shaped line in the H-L diagrams illustrates the hard-to-soft transition of XTE J1550–564 and is used for comparison with other sources.

Done 2003; Kubota & Done 2004). Then, the luminosity decreased at much slower rate, and spectrum softened even more, while the source reached the HS (left-hand) branch in the H-L diagram at HR $\sim$ 0.5. The entire transition from leaving the LH branch until reaching the HS branch took 54 days.

Panels (a–d) of Figs. 1 and 3 show the results from outbursts which we have categorized as the BS transition. They all begin in the LH branch of the H-L diagram, travel to the top 'cusp' at similar luminosity of $\sim$0.1 $L_{\rm Edd}$ and then move on to the HS branch. XTE J1550–564 and XTE J1859+226 had a flare (brighter in the former source) around the 'cusp'. In terms of the HR evolution (Fig. 3) they seem to begin the outburst with a fairly fast transition to the IM/VH state at HR $\sim$1.3, after which the transition to the soft branch is significantly slower. This is illustrated in Fig. 4. The transition to the IM/VH state takes about 5 days, while the full transition from LH branch to HS branch takes more than $\sim$30 days (see Table 2). These properties of the BS transition can be particularly clearly seen in XTE J1550–564 and XTE J1859+226.

GRS 1739–278 and H 1743–322 have limited statistics, but show many resemblances to the XTE J1550–564 H-L track, transition luminosity and duration of the transition. Alas, the distance to H 1743–322 is not known so its luminosity was calculated for the assumed distance of 8.5 kpc and we cannot make any claims about its actual luminosity. Their HR evolution, shown in Fig. 3(c) and (d), is similar to the two transitions shown in panels (a) and (b). Though errors on HR are substantially larger in GRS 1739–278 (Fig. 3c), its behaviour is entirely consistent with the BS transition. H 1743–322 shows a complex HR curve with the hard-to-soft transition repeated (Fig. 3d) immediately after reaching the soft branch. The first transition lasts 25 days, the total transition $\gtrsim$80 days.

The light curves of these outbursts can be complex in shape and generally long, extending over 200 days (with the exception of XTE J1859+226).

3.2 Dark/fast transition

Figs. 1(e–g) and 3(e–g) show three outbursts with quite different behaviour. They do not follow the XTE J1550–564 H-L track but make a 'shortcut' between the LH and HS branches at a much lower luminosity of $\lesssim$0.05 $L_{\rm Edd}$. The transition time is much shorter, taking less then 16 days (Table 2). While the BS transients slow down their rate of transition after reaching the IM/VH state at HR $\sim$ 1.3, the DF transients proceed to the soft branch at the same rate (see Fig. 4). The entire outburst seems to be shorter then in BS state transients.

XTE J1650–500 makes the most clear example of this transition, moving between the LH and HS branches at the luminosity of only about 0.02 $L_{\rm Edd}$ in about 16 days. The 2000 outburst of XTE J1550–564 was very different from its 1998 outburst. The transition was much shorter (about 7 days) and occurred at much lower luminosity. However, while during the 1998 outburst the source reached HR = 0.4 in the soft state (marked by a dashed line in Fig. 3e), the hardness ratio decreased only to 0.6 in 2000. Either it has not reached the 'proper' soft state at all, or the soft state was slightly different then in the 1998 outburst.

XTE J2012+381 is more problematic, as we do not know its distance, so the luminosity is calculated for the assumed distance of 8.5 kpc. However, its L-H evolution is very similar to the two other DF outbursts, both in track shape and speed of movement. Therefore, we classify this source as a DF transient.

Figs. 1(h) and 3(h) show the outburst of 4U 1543–47. It made a fast transition from the LH state to the unusually bright HS state, which might be due to its low inclination angle (see discussion in Sec. 4). However, the luminosity, duration of the transition and the evolution of hardness ratio allow us to classify this outburst as a DF transition.

Fig. 2 shows GX 339–4. In panel (a) we show the 2002/2003 outburst based on the most recent distance estimate of 8 kpc (Zdziarski et al. 2004). The light curve is long and complex, resembling BS transients. On the other hand, the shape of the H-L diagram, the hardness ratio evolution (Fig. 3i) and the fast transition time (9 days) strongly suggest the DF state transition. However, the transition luminosity $>$0.1 $L_{\rm Edd}$ is inconsistent with DF transitions. Additionally, both LH and HS branches are unusually bright, not consistent with any other source in our sample, except perhaps 4U 1543–47 (Fig. 1h). Another (2004/2005) GX 339–4 outburst, shown in Fig. 2(b) is less luminous, and perhaps consistent with DF transient behaviour.

In order to explain the unusual 2002/2003 outburst of GX339–4 we consider the possibility whether it can be still consistent with other DF transients within uncertainties of its mass and distance. Hynes et al. (2004) gave a fairly robust lower limit on the kinematic distance of 6 kpc. Cowley et al. (2002) gave the upper limit on the mass of 10 $M_\odot$. We use these two extremes to create a new plot, shown in Fig. 2(c) and (d). Clearly, both outbursts now seem to be consistent both in the track shape and transition luminosity with other DF transients. Though the entire light curve is more similar to other BS transients, the *transition itself* is short and marginally consistent with typical DF luminosity, so we tentatively classify GX 339–4 as a DF transient.

4 CAVEATS

In Sec. 3 we postulated existence of two distinct hard-to-soft spectral transitions in the initial part of the outburst of black hole transients. Our classification is based on the transition luminosity, duration, the shape of the track in the H-L diagram and the evolution of the hardness-ratio. Plainly, there are several uncertainties here. First of all, the luminosity strongly depends on highly uncertain distance and (to less extent) black hole mass. In Table 2 we show the range of luminosities due to the distance uncertainty. The uncertainties are large indeed, and there is an overlap between the two categories around $\sim$0.05 $L_{\rm Edd}$.

Another uncertainty comes from the interstellar absorption, affecting the derived luminosity and hardness ratio. Fortunately, most of sources analysed in this paper have moderate absorption column of $N_H \lesssim 10^{22}$ cm^{-2}. XTE J1739–278 and H 1743–322 have higher columns of about 2×10^{22} cm^{-2} (Greiner, Dennerl & Predehl 1996; Capitanio et al. 2005) which, depending on the shape of the spectrum can diminish the 1.5–12 keV flux down to $\sim$0.7 of the unabsorbed flux. The effect of this column on 3-12 keV hardness is negligible.

The luminosities quoted in this paper are calculated in the 1.5–12 keV energy band, but the bolometric luminosity is definitely larger. To estimate the bolometric correction in the IM/VH state we used the same physical model of XTE J1550–564 as in Sec. 2. It gives the bolometric luminosity 2.3 times larger then the 1.5–12 keV luminosity. Since the IM/VH spectra are similar in shape, this seems to be a good estimate of the bolometric correction factor. Thus, we estimate that the bolometric luminosity is $\sim$30 per cent of $L_{\rm Edd}$ during the BS transition and $\lesssim$10 per cent of $L_{\rm Edd}$ during the DF transition (though 4U 1543–47 transition is brighter, $\sim$16 per cent of $L_{\rm Edd}$, which might be due to its lower inclination angle,

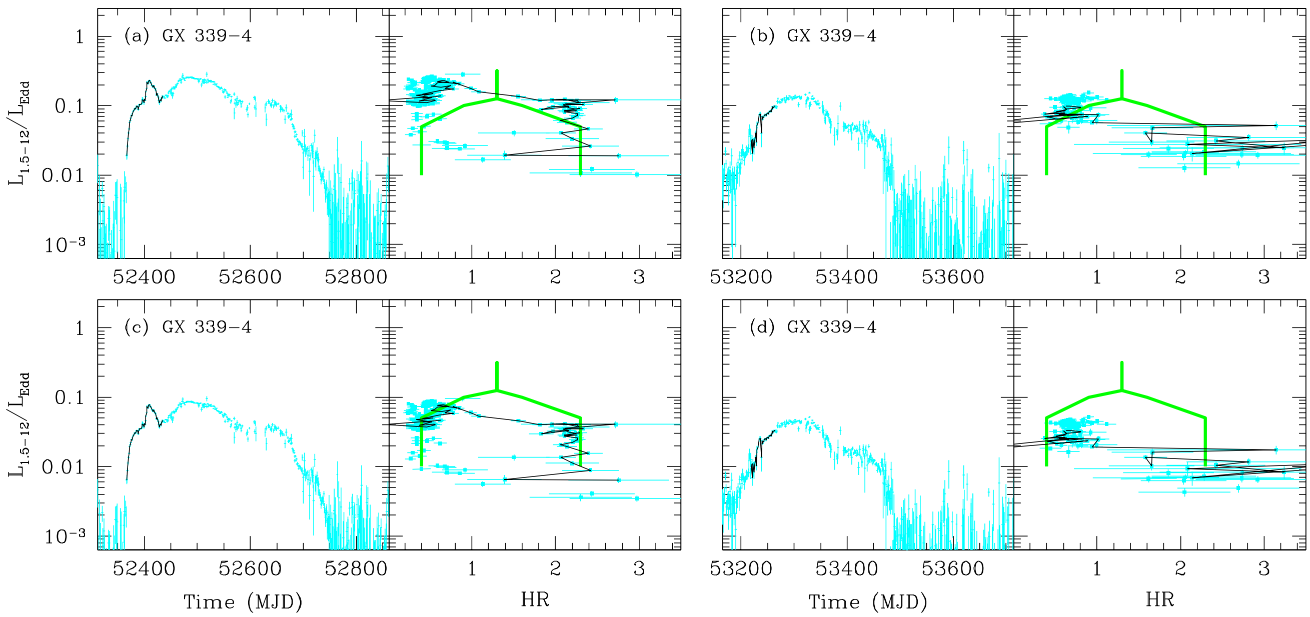

Figure 2. Light curves and H-L diagrams of GX 339–4. Left-hand panels, (a) and (b), show two outburst assuming the mass and distance from Table 1, i.e. 6 $M_\odot$ and 8 kpc, respectively. Right hand panels, (c) and (d), show the same outbursts calculated for the mass of 10 $M_\odot$ and distance of 6 kpc. The symbols and lines are the same as in Fig. 1.

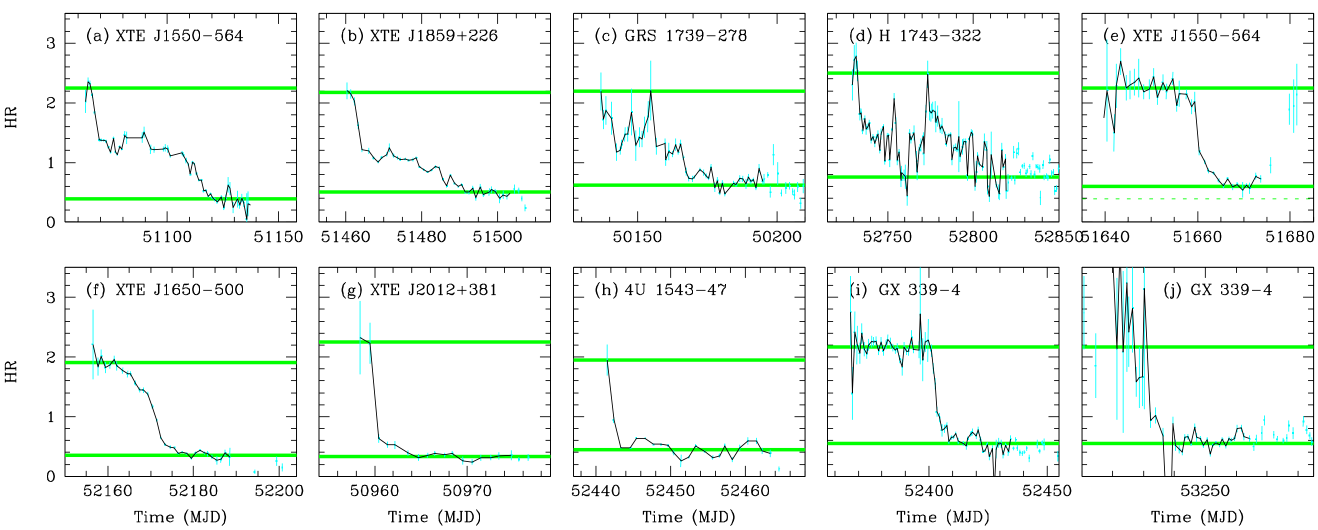

Figure 3. Evolution of the hardness ratio during the initial part of the outburst for several sources. The black lines connect the same points as in Figs. 1 and 2. The thick (green in colour) horizontal lines show our definition of the hard (upper line) and the soft (lower line) state for each source. The softest state of XTE J1550–564 achieved during the 2000 outburst (panel e) was harder then soft state in 1998 outburst (panel a), which is marked in panel (e) with a dashed line.

see next paragraph). We have performed similar tests for hard-state (observation id. 30188-06-01-00) and soft-state (30191-01-43-00) data and found bolometric corrections of 2.8 and 2.5, respectively.

The inclination angle of the accretion disc can play a significant role in the disc-dominated HS state. The emission from optically thin Comptonization, which dominates the LH state, is probably more isotropic, though it might be mildly boosted at low angles if it originates from a jet/outflow. Inclinations of the sources in our sample range (where known) between 21° for 4U 1543–47 (Park et al. 2004) and 72° for XTE J1550–564 (Orosz et al. 2002). We expect the apparent disc in the former source to be brighter by factor $\cos 21^\circ / \cos 72^\circ \approx 3$ then the latter one. This might explain why the HS branch of 4U 1543–47 is about 3 times brighter than in XTE J1550–564. The relatively low inclination of $(40 \pm 20)^\circ$ (Cowley et al. 2002) cannot account for the unusually high luminosity of GX 339–4, as it is also very bright on the LH branch.

Opportunely, all the caveats regarding distance, absorption and inclination angle can be dropped in the case of two different outbursts observed from *the same* source, XTE J1550–564. It displayed the BS transition in 1998 (Fig. 1a) and the DF transition in 2000 (Fig. 1e). Each outburst showed typical characteristics de-

Source Name	$L_{\rm trans}/L_{\rm Edd}$	$t_{\rm trans}$	Fluence	Type
XTE J1550–564[1a]	0.13 (0.04–0.28)	54	26	BS
XTE J1859+226	0.12 (0.05–0.14)	31	5.7	BS
XTE J1739–278	0.13 (0.06–0.21)	43	13	BS
H 1743–322	[$\sim$0.17]	25 or $\gtrsim$80	[17]	BS
XTE J1550–564[1e]	0.03 (0.01–0.07)	7	1.2	DF
XTE J1650–500	0.02 (0.01–0.05)	16	1.3	DF
XTE J2012+381	[0.02]	4	[3.7]	DF
4U 1543–47	0.07 (0.06–0.08)	2	9	DF
GX 339–4[2a,2c*]	0.15 (0.11–0.21) or 0.05*	9	49 or 16*	DF?
GX 339–4[2b,2d*]	0.06 (0.04–0.08) or 0.02*	$\sim$8	21 or 7*	DF?

Table 2. Transition luminosity (in Eddington luminosity), transition duration (in days) and outburst fluence (in days) for sources where transition was observed. The transition luminosity was read from the colour-luminosity diagram at HR = 1.25, corresponding to a 'cusp' in the XTE J1550–554 diagram. The luminosity range was given for the distance range in Table 1. The numbers in square brackets correspond to the assumed distance of 8.5 kpc. Superscripts in the first column denote different outbursts, referring to figure numbers. Asterisks mark the distance to GX339–4 of 6 kpc and its mass of 10 $M_\odot$, as opposed to the quantities listed in Table 1

rived for each transition category, which significantly strengthens our result.

One possible uncertainty comes from the identification of the soft- and hard-state branches, which can subsequently affect measurements of the transition duration. Usually, the spectral state of an X-ray source is established on the basis of its spectral *and* variability properties. In this work we define the hard and soft state branches on the sole basis of their hardness ratio, which might not necessary agree with the full spectral/timing definition. In particular, ASM data show that XTE J1650-500 reached the HS branch at HR = 0.35 around MJD 52176. We have calculated the same hardness ratio from available PCA data and found it to be in perfect agreement with the ASM data. However, after the transition, around MJD 52190 (see Fig. 4f), where the ASM data are sparse and of poor statistics, PCA shows a further decrease in the hardness ratio to about HR = 0.15. Rossi et al. (2004) classified the state at HR = 0.35 as the very high state, but they also noted that its properties were quite different from the IM/VH state during the transition. A similar situation is in the case of the 2000 outburst of XTE J1550–564, which never reached the soft state similar to that in 1998. It is then possible, that our HS branch derived from the ASM data contains softer IM/VH states, as defined from the spectral and variability properties. Thus, the transition time from the hard state to the *true* soft state can be longer then the transition between the ASM LH and HS branches, derived in this paper.

This, however, does not seem to affect our main result about the difference between the BS and DF transitions. The transition between the LH and HS branches, *as derived from ASM data*, is markedly faster and less luminous in DF transients. Even if our HS branch does not exactly correspond to the true soft state, there is still a *systematic* difference between those transitions, as illustrated in Fig. 4.

We would like to stress, that despite all the caveats discussed in this section, there are two criteria distinguishing between the DF and BS transitions, which are fairly robust. These are the duration of transition between LH and HS branches (or evolution of the hardness-ratio) and the shape of the L-H track. Though in some cases the limited statistics makes recognizing the track rather difficult, we find that when all the clues are taken together, there is a significant, systematic difference between the two categories of transitions. Therefore, we find our classification robust and well defined.

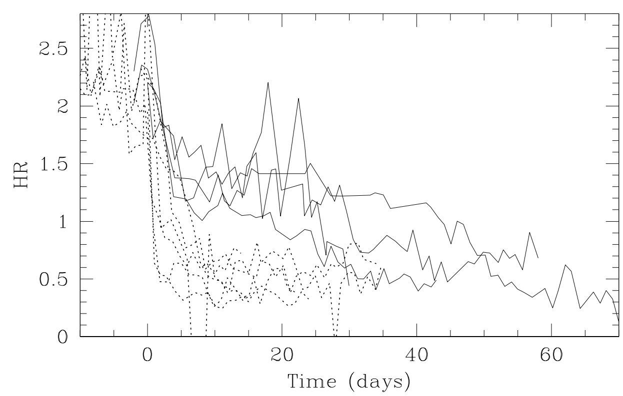

Figure 4. Comparison of the hardness ratio evolution of all transitions shown in Fig. 3 (the second transition of H 1743–322, after MJD 52762, was omitted for clarity), zeroed at the beginning of the hard-to-soft transition. Solid curves represent BS transitions and dotted curves represent DF transitions. This figure illustrates the crucial difference between the two types of transitions. After the initial fast phase, the BS transition is much slower after reaching HR $\sim$ 1.3, while DF transients continue to the soft branch at the same rate.

5 DISCUSSION AND CONCLUSIONS

We have studied light curves and hardness-luminosity diagrams of several GBH transients. We have found two distinct categories of spectral transitions occurring after the initial hard state during the rise of the outburst and before the disc-dominated high/soft state. The bright/slow transition reaches the estimated bolometric luminosity of 0.3 $L_{\rm Edd}$ or more. The initial transition from the LH state is fast, but it is significantly slowed down after reaching the bright IM/VH state. The entire transition to the HS state takes over 30 days. The LH and HS branches in the H-L track are connected by a roughly semi-circular, counter-clockwise track. The dark/fast transition typically takes place at luminosities $\lesssim$0.1 $L_{\rm Edd}$, it is faster (less then $\sim$15 days), does not slow down at the IM/VH state and makes a 'shortcut' between the LH and HS branches in the H-L diagram. The difference between these two categories is shown in Fig. 5.

The distinction between the two categories seems to be clear, and can be particularly well seen in Fig. 4. However, we only have four transitions in each category, so from purely statistical point

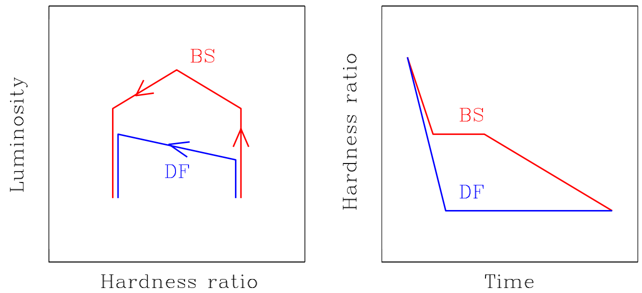

Figure 5. Schematic diagram of two types (bright/slow and dark/fast) of hard-to-soft transitions. Left panel: hardness-luminosity diagram. Right panel: evolution of the hardness ratio.

of view the bimodal behaviour is not yet significant. Plainly, more data is necessary to firmly confirm our discovery.

The terms 'very high' and 'intermediate' state have been used in the literature (e.g. Miyamoto et al. 1991; Homan et al. 2001), and sometimes the distinction between the higher and lower luminosities had been made (e.g. Méndez & van der Klis 1997). Later, this distinction was abandoned, when it became clear that the IM/VH states can occur at various luminosities, often less than that in the disc-dominated HS state. Instead, the definition based on both spectral and timing properties was proposed (e.g. McClintock & Remillard in press). The energy and power spectra of these states are similar, regardless of luminosity (e.g. Homan et al. 2001; Kalemci et al. 2003; Gierliński & Done 2003; Montanari, Frontera & Amati 2004). No systematic distinction between bright and dark IM/VH spectral states has been found so far. In this paper we have shown that the hard-to-soft state transition can take place at two different luminosities, and that there is a systematic difference between the low- and high-luminosity transitions. If physical properties of the accretion flow are different between the DF and BS transitions, then we might expect some difference in the spectral state as well. If this were true than perhaps the distinction between the IM and VH states might be valid, after all. Confirming this potential difference would require additional studies.

There are certain limitations to the BS/DF distinction we have proposed in this paper. The estimated BS transition bolometric luminosity of $\sim$0.3 $L_{\rm Edd}$, observed in the four sources shown in Fig. 1(a–d), is not entirely typical, and can be easily surpassed. Some of the transients reached and exceeded the Eddington luminosity during their outbursts, e.g. V404 Cyg (e.g. Życki, Done & Smith 1999), Nova Mus (Życki et al. 1999), or V4641 Sgr (Revnivtsev et al. 2002). GRS 1915+105 is also known to be very bright (Done, Wardziński & Gierliński 2004), but it is a rather untypical transient (Truss & Done 2006). It is interesting to notice that GX 339–4 made two transitions at significantly different luminosity, but with time-scales and hardness ratio evolution typical for DF transitions. Thus, the DF transition luminosity is not constant and the transition can occur at a range of luminosities below a certain critical value. The opposite, i.e. a range of luminosities above a critical limit, could be true for the BS transitions. It is difficult to ascertain using currently available data, whether these two critical luminosities are equal or not.

We have seen both types of transitions from the same source, XTE J1550–564. This obviously means that the outburst type is not predestined by the properties of the binary, such as the disc size, the orbital period or mass/spin of the black hole. The distinguishing factor must be hidden in the accretion flow itself. The numerical model of the disc instability by Dubus, Hameury & Lasota (2001) shows that two types of outbursts can develop in the accretion disc, depending on the radius at which the hydrogen ionization instability is triggered. When the ignition radius is small (the 'inside-out' outburst) the propagation time of the inward heating front is short, while the outward front can easily stall in the regions of higher density, which leads to short, low-amplitude outbursts. When the ignition radius is large, (the 'outside-in') outburst, the inward front progresses through regions of decreasing density and can heat the whole disc, leading to longer, brighter outbursts.

This, in principle, could explain the difference between bright and dark transitions/outbursts. However, we can see from the light curves that the length of the outburst is not simply correlated with its amplitude. Though generally BS outbursts have longer and more complex light curves then DF outbursts, there are a few exceptions. For example XTE J1859+226 (Fig. 1b) and XTE J2012+381 (Fig. 1g), have light curves very similar in shape and duration, despite undergoing different types of LH-HS transition. GX 339–4, tentatively categorized as a DF transient, displays very long and complex light curves.

Perhaps a better quantity that could distinguish between 'inside-out' and 'outside-in' outbursts is the fluence, which is a rough estimate of the total amount of the accreted material. We have estimated the fluence of each outburst (Table 2). BS outbursts tend to have larger fluence, though the distinction is not unique. For example, the BS outburst of XTE J1748–288 has smaller fluence then the DF outburst of XTE J2012+381, though distances and BH masses of both sources are not known, so this estimate is very uncertain. And again, GX 339–4 does not easily fit into the picture with its large fluence, even assuming extreme black hole mass and distance, as in Sec. 4. Clearly, the radius at which the initial instability occurs can be an important factor, but does not entirely explain the observed properties of spectral transitions.

Thus, it seems that the total amount of accreted material in an outburst does not predestine the type of the LH-HS transition. The clue to the distinction between the DF and BS transitions might lay in the irradiation of the disc by the central source. Irradiation can lengthen the bright state of the disc (King & Ritter 1998). At the same time, it can increase evaporation rate (Różańska & Czerny 2000; Meyer-Hofmeister, Liu & Meyer 2005; Dullemond & Spruit 2005), which in turn can help sustaining the bright corona providing the source of irradiation. An interesting feature of the observed outbursts is that the initial transition to the IM/VH state takes roughly the same time, irrespectively of the luminosity, and only after that transitions diversify into slow and fast, for high and low luminosities, respectively. We speculate, that the luminosity in the IM/VH state defines the type of the LH-HS transition. When it reaches $\gtrsim$0.3 $L_{\rm Edd}$ it triggers the self-sustaining bright corona, and prolongs the bright BS transition. The dimmer and much shorter DF transition does not reach the luminosity required to lengthen the bright state and sustain the corona, so it disappears and the source quickly moves on to the disc-dominated HS state.

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